Acoustic Remote Sensing of Large-Scale Temperature Variability in the North Pacific Ocean

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***Abstract* — Large-scale, depth-averaged temperatures have been measured by long-range acoustic transmissions in the North Pacific Ocean for the past nine years. Acoustic sources located off central California and north of Kauai transmitted to receivers distributed throughout the North Pacific from 1996 through 1999 during the Acoustic Thermometry of Ocean Climate (ATOC) project. The Kauai transmissions resumed in early 2002 and are now continuing as part of the North Pacific Acoustic Laboratory (NPAL) project; a six-year time series has been obtained so far. Even at long time and large spatial scales the ocean is highly variable. The paths from Kauai to California show a modest cooling trend (longer travel times) until the present time. A path to the northwest showed modest warming and a weak annual cycle from 1999 until early 2003, when a strong annual cycle returned. In retrospect, these changes stemmed from the warming of the central Pacific that occurred in this interval, possibly associated with the Pacific Decadal Oscillation (PDO). Comparisons between measured travel times and those predicted using ocean models, constrained by satellite altimeter and other data, show significant similarities and differences. Comparison between upper-ocean Argo profiling float temperatures and the acoustically measured temperature along one path illustrates the strength of the integral measurements, with substantially lower uncertainty. The acoustic data ultimately need to be combined with sea-surface height Argo float data to determine the complementarity of the various data types. In particular, combining the acoustic and Argo data by inverse techniques will quantify the ability of the float data to resolve large-scale, upper-ocean heat content and the ability of the acoustic data to resolve abyssal temperature changes.**

I. INTRODUCTION

Ocean acoustic tomography was introduced by Munk and Wunsch in 1979 as a tool for observing the energetic ocean mesoscale. This was extended to basin scales, complemented by satellite altimetry, and was made specific to measuring basin-scale climate change signals in the form of thermometry, leading to the Acoustic Thermometry of Ocean Climate (ATOC) project [1, 2]. Thermometry may be thought of as a subset of tomography. With the latter, multiple crossing paths are used to obtain spatial resolution, whereas with the former, a sparse set of paths are used to obtain a good measure of the mean, with the mesoscale "noise" largely averaged out by the path integral properties of the measurement. Given the realities associated with instrument placement, there are elements of both in the present North Pacific Acoustic Laboratory (NPAL) array (Fig. 1).

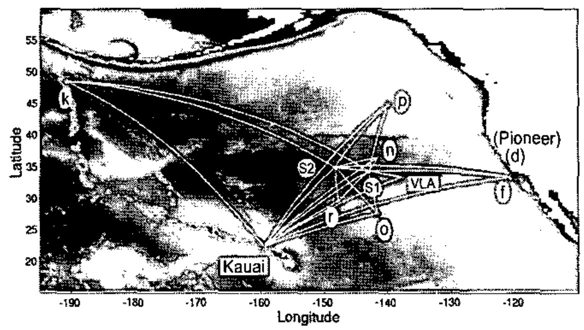

Fig. 1. The present NPAL array. For 2004–2005, it is augmented by the vertical line array (VLA) and transceivers S1 and S2.

A major goal of basin-scale acoustic thermometry is to obtain high precision estimates of average heat content and temperature. The motivation is that the oceans are by far the largest reservoir of heat in the global climate system; as has been oft said, they are the flywheel of climate. As pressures on the environment grow, it will be necessary to monitor this reservoir with increasing accuracy and precision. A worthy goal would be to measure the ocean annual cycle and longer term variation of equivalent heat flux to a fraction of 1 W m^{-2} over a year (~ 1.5×10^{22} J averaged over the area of the whole Earth).

Levitus et al. [3] examined the temperature variations in the ocean basins over the past 50 years using all available historical hydrographic data (5 million profiles, on average 100,000 per year). Time series of temperature variations in the ocean basins were obtained by averaging temperature over entire ocean basins, and then calculating 5-year running means of the time series (Fig. 2). The estimated uncertainty in 0–1000-m average temperature obtained for the North Pacific was about ±0.01°C (not including uncertainties caused by undersampling, apparently), comparable to the formal uncertainty in temperature derived acoustically on a single day on a single acoustic path. More recently Argo floats are being deployed and roughly the same number of profiles are expected per year, albeit more uniformly distributed.

Here we compare the acoustic measurements in the North Pacific with data assimilating model results and Argo float measurements.

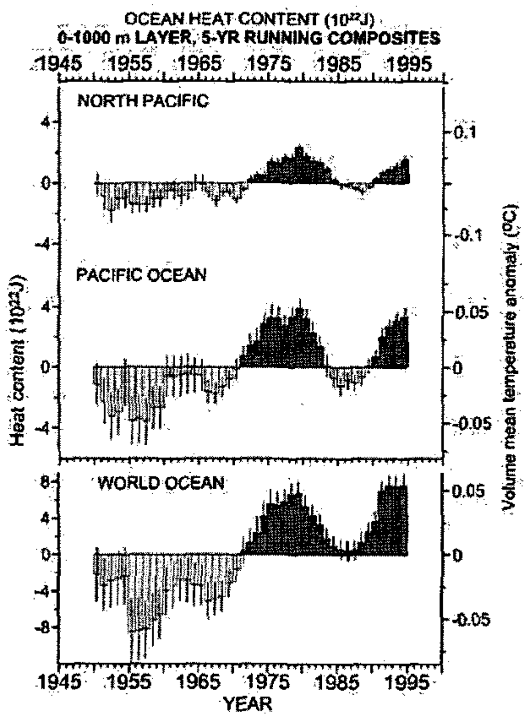

Fig. 2. Changes in heat content and temperature, adapted from Levitus et al., 1999. Vertical lines are standard errors. Note scale changes.

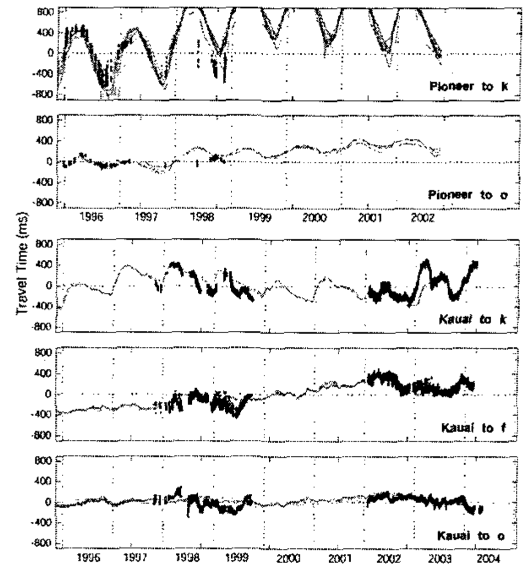

Fig. 3. Travel times measured on the 1–5-Mm-long acoustic paths compared to travel times predicted using the JPL-ECCO ocean model. See Fig. 1 for path identification. Six to twelve rays are resolved and identified on each acoustic path.

II. COMPARISON WITH ECCO OCEAN STATE ESTIMATES

The analysis of path integral data is made much simpler by modern ocean state estimation methods, using travel times as integral constraints on the model variability. If the data estimated by the model do not match the observations, then the ocean model state is adjusted to bring the model into better agreement. As implemented by the ECCO Consortium (Estimating the Circulation and Climate of the Ocean) and others [4, 5], state estimation also serves to best combine disparate data types, which can then be evaluated for their contributions to reducing the uncertainty of the solution.

As a first step towards incorporating travel times into the ECCO model cost function, ECCO model output was converted into travel times for several source-receiver pairs (Fig. 3). Different ray paths have different sensitivities to the surface and to the deep ocean, and the estimation can exploit this to obtain vertical information from a set of rays.

The ocean state estimate used here is based on an integration of the MIT General Circulation Model in a global configuration that spans 75° S to 75° N, with latitudinal grid spacing ranging from 1/3° at the equator to 1° at the poles and longitudinal grid spacing of 1°. The model assimilates a variety of satellite and in-situ data and data products, including TOPEX/POSEIDON, WOCE hydrography, XBT sections, and Argo float data. A description of this state estimate and the complete fields are available at http://eyre.jpl.nasa.gov/external.

The original ECCO optimization described by [6] adjusted the forcing and initial conditions of a 2° resolution version of the classic MIT GCM so as to match the model output to the altimeter observations. More recently, a 1° version of the model has been optimized to match hydrographic data (CTDs, XBTs and float profiles) as well as altimetry. The travel times calculated from the 1° optimized model output differ significantly from the travel times calculated for the 2° optimized model, showing that the acoustic data contain significant information about subsurface ocean structure.

In general, the variability in the model and the data show similarities and differences (Fig. 3). One immediate correction to both runs of the model required by the acoustics was its time mean state (not shown). The model sound speeds gave unphysical results when used for acoustic calculations, so the time mean state of the model was replaced by the World Ocean Atlas.

III. THERMOMETRY AND ARGO FLOAT DATA

Argo profiling float data have become available in the past few years for comparison with acoustic time series. The Kauai to k acoustic path (Fig. 1) is used to directly compare ATOC and Argo hydrographic line averages of temperature. All float profiles within 300 km of the acoustic path were first extracted. Figs. 4 and 5 show the horizontal and vertical sampling in a 10-day snapshot. The annual mean World Ocean Atlas temperatures were then subtracted to remove most of the geographical variations in temperature and to focus on the "anomalies". The resulting temperature profile anomalies were depth-averaged, and these in turn were averaged together on 10-day intervals—insofar as this was possible (many of the floats early in the time series are shallow). The acoustic travel measurements were inverted using a simple statistical ocean model consisting of six modes including a mixed layer to represent vertical variability and a red spectrum with 20 wave numbers to represent horizontal variability; the variance in the main thermocline was ~ 1° C.

The direct comparison between the float "path averaged" temperatures and the ATOC derived temperature measurement is shown in Fig. 6. Here, the thin vertical magenta bar gives the standard deviation of the vertical averages of the float profile data within the area in a 10-day interval, ±0.6° C. An estimated uncertainty for the Argo volume mean is this standard deviation divided by the square root of the number of samples in the 10-day interval (~20); this is shown by the heavy magenta bar, ±0.15° C. The corresponding uncertainty in the ATOC derived temperature from the inversion process is ±0.02° C. This substantially lower uncertainty is a direct result of the path averaging inherent in the acoustic measurement (Fig. 5). The difference between the Argo and ATOC determined average temperatures is ~30–50 percent of the annual cycle, within the uncertainty estimates and consistent with both measurements.

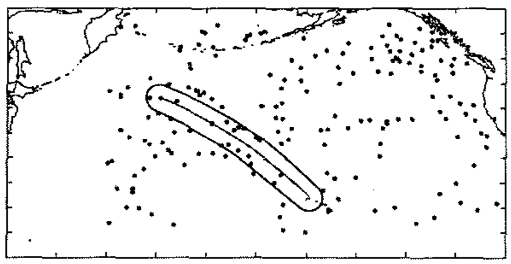

Fig. 4. Acoustic path from Kauai to receiver k with positions of the available Argo floats during a 10-day period in fall 2003.

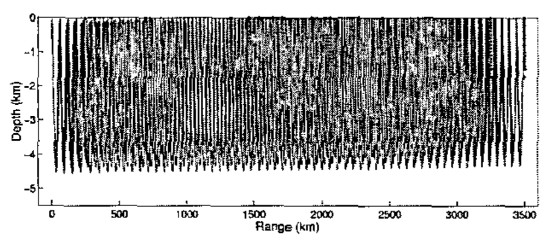

Fig. 5. Sampling for path Kauai–k ray (propagation time ~2000 s, six times every fourth day) and 16 Argo float profiles (10 days). The hydrographic and acoustic sampling in time and space are not the same.

The Argo profiles of temperature show great variability, reflecting the internal wave and mesoscale variability of order 1° C. This variability can make detection of oceanic climate change with point measurements difficult. The acoustic time series are smoothed only by forming a daily average of travel time.

IV. CONCLUDING REMARKS

The optimal way to compare and combine the Argo and ATOC data is to use an objective mapping approach, similar to the inversion method mentioned above, but including more resolution in the vertical, horizontal, and (in a simple way) time. This will permit a rigorous treatment of internal waves "noise" and mesoscale and larger-scale variability. This work is in progress.

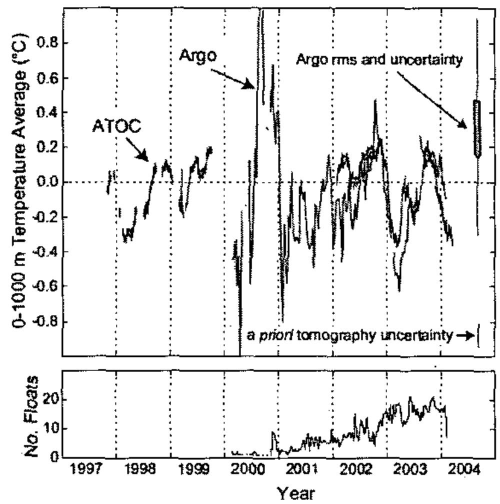

Fig. 6. Timeseries of range- and depth-averaged temperature derived from acoustic thermometry and from Argo float data.

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